

DESIGN CONSIDERATIONS FOR ATTITUDE STATE AWARENESS AND PREVENTION OF ENTRY INTO UNUSUAL ATTITUDES

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Loss of control – inflight (LOC-I) has historically represented the largest category of commercial aviation fatal accidents. A review of the worldwide transport airplane accidents (2001-2010) evinced that loss of attitude or energy state awareness was responsible for a large majority of the LOC-I events. A Commercial Aviation Safety Team (CAST) study of 18 worldwide loss-of-control accidents and incidents determined that flight crew loss of attitude awareness or energy state awareness due to lack of external visual reference cues was a significant causal factor in 17 of the 18 reviewed flights. CAST recommended that “Virtual Day-Visual Meteorological Condition” (Virtual Day-VMC) displays be developed to provide the visual cues necessary to prevent loss-of-control resulting from flight crew spatial disorientation and loss of energy state awareness. Synthetic vision or equivalent systems (SVS) were identified for a design “safety enhancement” (SE-200). Part of this SE involves the conduct of research for developing minimum aviation system performance standards (MASPS) for these flight deck display technologies to aid flight crew attitude and energy state awareness similar to that of a virtual day-VMC-like environment. This paper will describe a novel experimental approach to evaluating a flight crew’s ability to maintain attitude awareness and to prevent entry into unusual attitudes across several SVS optical flow design considerations. Flight crews were subjected to compound-event scenarios designed to elicit channelized attention and startle/surprise within the crew. These high-fidelity scenarios, designed from real-world events, enable evaluation of the efficacy of SVS at improving flight crew attitude awareness to reduce the occurrence of LOC-I incidents in commercial flight operations.

Recent data indicate that Loss-Of-Control In-Flight (LOC-I) accidents are the leading cause of commercial aviation accidents and incidents today (Boeing, 2016). Recent analysis by the Commercial Aviation Safety Team (CAST, 2014a) showed that LOC-I is primarily comprised of two causal factors: Spatial Disorientation (SD) and Loss-of-Energy State Awareness (LESA). SD is defined as an erroneous perception of aircraft attitude that can lead directly to a LOC-I. LESA is typically characterized by a failure to monitor or understand energy state indications (e.g., airspeed, altitude, vertical speed, commanded thrust) and a resultant failure to accurately forecast the ability to maintain safe flight. The leading consequence of LESA is aircraft stall.

To address the safety concerns surrounding LOC-I, CAST formulated a Joint Safety Analysis Team (JSAT) to study 18 recent LOC-I events. The JSAT study determined that a lack of external visual references (i.e., darkness, instrument meteorological conditions, or both) was associated with flight crew loss of attitude awareness or energy state awareness in 17 of these events (see Figure 1). A Joint Safety Implementation Team (JSIT) was formed to address the safety concerns identified in the JSAT study (CAST, 2014b). CAST recommended that, to provide visual cues necessary to prevent LOC-I, manufacturers should develop and implement virtual day- visual meteorological condition (VMC) display systems, such as synthetic vision systems. In support, CAST requested the National Aeronautics and Space Administration (NASA) to conduct research and lead efforts to support definition of minimum aviation system performance standards (MASPS) for virtual day- VMC displays to accomplish the intended function of improving flight crew awareness of airplane attitude. CAST established Safety Enhancement 200 (SE-200) entitled, “Airplane State Awareness – Virtual Day-VMC Displays” to formalize this effort.

Airplane State Awareness – Virtual Day-VMC Displays

The purpose of SE-200 is to reduce the risk of LOC-I by having manufacturers develop and implement virtual day-VMC display systems (such as SVS) that will support flight crew attitude awareness similar to a day-VMC-like environment in applicable new transport category airplane programs. SE-200 includes a detailed implementation plan that defined specific research needs to support the design and implementation of these displays that will enable the necessary visual cues to prevent LOC-I due to flight crew SD/LESA and aid in detecting unusual attitude entry and performing recovery. In large transport aircraft, an unusual attitude is operationally defined as a nose-up pitch attitude greater than 25 degrees, a nose-down pitch attitude greater than 10 degrees, a bank angle greater than 45 degrees or flight within these parameters but with airspeeds inappropriate for the conditions.

Virtual day-VMC display standards are not currently in effect for this intended function and the NASA research will inform the development of MASPS under RTCA Special Committee (SC)-213, Enhanced Flight Vision Systems and Synthetic Vision Systems (EFVS/SVS).

Virtual Day-VMC Displays

Virtual day-VMC displays are intended to provide similar visual cues to the flight crew that are available when outside visibility is not restricted (i.e., often observed under VMC). Their intended function would be to improve continuous attitude, altitude, and terrain awareness, reducing the likelihood of unstable approach, inadvertent entry into an unusual attitude, spatial disorientation, and/or collision with terrain through a synthetic vision (SV) display. SV is a computer-generated image of the external scene topography from the perspective of the flight deck, derived from aircraft attitude, high-precision navigation solution, and database of terrain, obstacles, and relevant cultural features

Technologies for Airplane State Awareness

The SE-200 detailed implementation plan defined areas of research needs for design and implementation of virtual day-VMC displays to prevent loss-of-control accidents due to loss of attitude awareness and lack of external visual references. The NASA “Technologies for Airplane State Awareness” (TASA) project was created to address SE-200 and other safety enhancements. NASA research has been completed that evaluated design characteristics such as image minification, optical flow cues, and field-of-view (Nicholas, 2016). The present paper describes high-fidelity, large commercial transport simulation research that evaluated various types of SVS displays for their efficacy to improve attitude awareness and prevent unusual attitude (UA) conditions from developing during realistic flight operations scenarios.

Experimental Method

Research Pilots

Twelve current major commercial airline pilot crews participated in the research. The average experience was 22,000 hours. Pilots were required to have 737/A320 or larger aircraft type ratings from major domestic airlines, with preference given to those with glass cockpit experience.

Research Simulator

The research was conducted in the Research Flight Deck (Figure 1) at NASA Langley Research Center, which is a high-fidelity, 6 degrees-of-freedom motion-based large commercial aircraft simulator with full-mission capability and advanced glass, Boeing 787-like flight deck displays.



Figure 1. Research Flight Deck Simulator

Special Purpose Operations Training Scenarios

The research employed four special purpose operations training (SPOT) scenarios based on FAA training guidance (FAA Advisory Circular 120-35D). NASA and subject matter experts designed the four SPOT scenarios using a sequence of off-nominal events that create challenging flight and workload conditions that may ultimately lead to an unusual attitude without timely pilot intervention. The compound failures required pilots to address several issues, often unrelated, that saturated the pilot's/crew's attention. The SPOT scenarios stressed the crews' aircraft state awareness to evaluate the efficacy of the display system to maintain pilot attitude awareness and identify recognition of impending unusual aircraft attitude conditions.

The four SPOT scenarios were: (1) False-Glideslope with Radar Altimeter Fail; (2) Fuel Leak with Clear Air Turbulence; (3) Reduced Engine Performance/High-Alpha; and, (4) Missed Approach with Degraded Autopilot in the roll axis.

In addition to the SPOT scenarios, nearly identical distractor scenarios were created for each of the four SPOT scenarios but with the removal of one or several off-nominal events. These additional scenarios were challenging, requiring significant pilot interaction, but did not lead to an unusual attitude conditions.

Special Purpose Operations Training Experimental Method

Eight scenarios, four SPOTS and four distractor scenarios, were evaluated in an ordered sequence - the crews flew the SPOT scenario prior to the distractor scenario of similar type. Because the SPOT scenarios involved "black swan" events, they could only be presented once to successfully achieve the high level of task saturation and surprise required for the experiment (Taleb, 2007). The crews were assigned to one of four experimental blocks with each block given a different display condition for each scenario. The scenario order was fixed across all crews, randomized by display condition block in a between-subjects design. Scenarios lasted on average eight minutes.

The purpose of the test was to evaluate a flight crew's ability to maintain attitude awareness and prevent entry to unusual attitudes. Pre-experimental briefings provided instructions and training including FAA- (FAA, 2016) and Boeing- (Boeing, 2004) recommended UA recovery (UAR) techniques. Pilots were briefed about evaluations of the displays, not the off-nominal nature of the scenarios. This training is in addition to the training that the pilots have received with their respective airlines.

Display Concepts

The experimental display concept conditions are shown in Figure 2. The Baseline display emulated a Boeing 787-like primary flight display (PFD); this display does not include SV. Three virtual-day VMC (SVS) display concepts were used - one was representative of the MASPS, as defined by RTCA under DO-315A, for a synthetic vision display intended for terrain awareness (i.e., the so-called "SVS1- MASPS"). The other SV concept was representative of the Industry Standard virtual-day VMC (SVS) in operational use today (i.e., the so-called "SVS-2 - Industry"). The SVS3-Advanced display concept was the industry standard (SVS2) with an added innovative optical flow cue designed to aid situation awareness when the aircraft enters an unusual attitude. If no unusual attitude condition is present, the display is effectively the same as the industry standard type. All display concepts included roll arrow recovery guidance (Ewbank et al, 2016) and angle-of-attack indication (Cashman et al,

2000) (note: angle-of-attack indicator is standard on B-787 PFDs). The roll arrow guidance symbology is displayed when the aircraft attitude meets roll angle exceedance criteria (see Figure 3).



Figure 2. Experimental Display Conditions

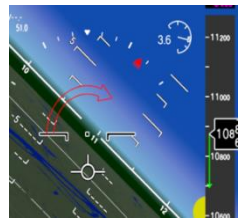


Figure 3. Roll Arrow Recovery Guidance and Angle-of-attack (Alpha) Symbologies

Experimental Results

The crew was informed of the initial flight condition and the display concept being flown. All flights were conducted with Memphis as the destination airport. The SPOT was orchestrated by pre-programmed non-normal events to induce the unusual attitude conditions. Once the recovery was completed, the trial ended and post-trial subjective scales were administered and pilot comments solicited. Post-scenario questionnaires were administered, including the NASA-Task Load Index (TLX) evaluation of workload, a three-question Situation Awareness Rating Technique evaluation of Situation Awareness (SA), and single score evaluation of crew-member workload.

Quantitative Results

Several dependent measures were assessed during specific time windows leading up to, during, and immediately after the unusual attitude events. These data revealed that SPOT-2 and SPOT-4 were the most effective in achieving pilot crew surprise and task saturation to properly evaluate the display conditions.

The SPOT-2 UA condition was induced by an autopilot disconnect (due to a fuel imbalance) followed by a near-simultaneous clear air turbulence event. Both events required pilot intervention to maintain attitude control. Time-to-first correct input distributions for SPOT-2 are shown below in Figure 4. Analysis show nearly significant results ($p < 0.05$) for time-to-first correct roll input across display condition, $F(3, 8) = 3.44$, $p = 0.072$. Results were not significant for time-to-first correct pitch input $F(3,8) = 2.15$, $p = 0.172$.

The SPOT-4 scenario involved a degradation in the roll-axis autopilot, occurring while the aircraft was turning following a missed approach vector from the tower. This resulted in pilots expecting the aircraft to turn based on the commanded heading setting on the autopilot, however, the aircraft would continue to roll beyond 45 degrees of bank without pilot intervention due to the un-annunciated degraded autopilot condition. Data was evaluated from the moment the autopilot was degraded in the roll-axis and the 15 seconds following that event. Time- to-first correct input distributions for SPOT-4 are shown below in Figure 5. No statistically significant results were observed across the four display conditions for time-to-first correct pitch input $F(3,8) = 2.36$, $p = 0.148$, or for the time-to-first correct roll input $F(3,8) = 1.48$, $p = 0.291$.

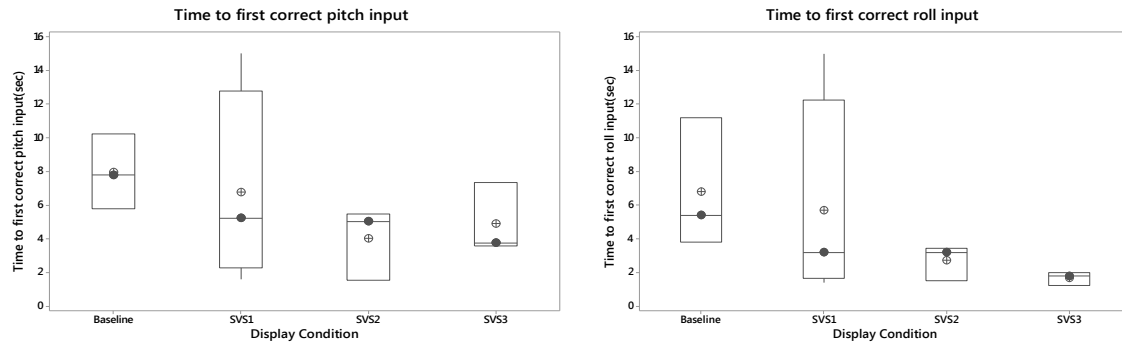


Figure 4. SPOT 2 Time-to-First Correct Pitch and Roll Input

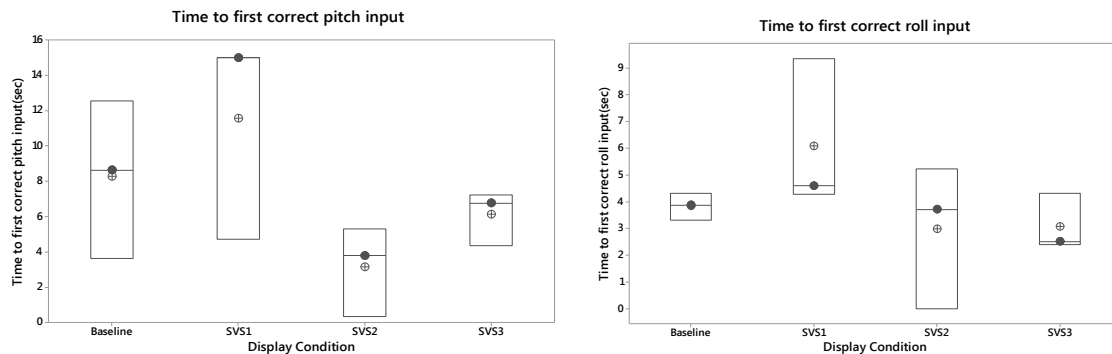


Figure 5. SPOT 4 Time-to-First Correct Pitch and Roll Input

Qualitative Results

NASA-Task Load Index. No significant differences were found across display concepts for NASA Task Load Index (NASA-TLX) for any of the presented SPOT scenarios.

Situation Awareness Rating Technique. No significant differences were found across display concepts for Situation Awareness Rating Technique (SART) for any of the presented SPOT scenarios.

Paired Comparisons. A mixed-factor ANOVA was conducted on the independent variables of display type (Baseline, SVS1, SVS2, SVS3) and pilot role (First Officer, Captain). The ANOVA revealed a significant main effect for display concept, $F(3,36) = 17.291$, $p < 0.001$ and display-role interaction, $F(3,36) = 3.15$, $p < 0.05$. The main effect of role was not significant, $F(1,12) = 0.143$, $p > 0.05$. Post-hoc simple effects analysis evinced that Baseline, SVS1, SVS2, and SVS3 were not significantly different. However, SVS2 and SVS3 were significantly different from Baseline and SVS1.

Main Effect for Display Concept. The results suggest that both the Captain and First Officer rated the advanced synthetic vision display concepts (SVS2 and SVS3) higher for attitude awareness than either the baseline or lower fidelity SVS display concept. However, the addition of “optical flow” (SVS3) did not enhance the SA ratings compared to the industry standard SV concept (SVS2).

Interaction Effect for Display Concept x Role. The significant interaction revealed that the First Officer provided significantly higher paired comparison ratings for the SVS2 and SVS3 concepts. Although the Captain rated the SVS2 and SVS3 significantly higher than the baseline or SVS1 concepts, the First Officer provided the most significant contrast in ratings as they tended to provide lower ratings than Captains for the baseline and SVS1 concepts but much higher ratings for SVS2 and SVS3. The results suggest that the advanced features of the SVS2 and SVS3 were more beneficial for SA for the monitoring pilot (First Officer). Although both pilots rated the SVS2

and SVS3 displays higher in terms of SA, the Captains did not statistically rate the SVS1 as higher than the SVS2 or SVS3, but did rate all three SVS concepts higher than baseline. The First Officers however, provided that the baseline and SVS1 concepts were statistically equivalent for SA but there was a substantial SA increase for SVS2 (highest) and SVS3 and the differential pattern of results accounts for the significant display-role interaction.

Conclusions

The pilots that participated in the research had substantial experience and training in recognizing and recovery from unusual attitudes. The pilot population was conservatively selected because it was hypothesized that, if significant differences were found across displays, it would be even more significant with less experienced commercial pilots (i.e., the identified risk group in the CAST report). The limited number of trials presented to each of the pilot crews does not allow for any statistical evidence to generalize to the commercial pilot population. However, these data do provide indications that are useful in evaluating pilot response in extremely rare circumstances such as presented in the SPOT scenarios.

The performance data suggest there may exist an operational improvement in UAR, as indicated by the pilot's time-to-first correct roll input when using the Industry Standard (SVS2) and Advanced (SVS3) SVS display concepts. These results show that pilots generally had faster correct control inputs while using SVS concepts that included higher definition details such as terrain texturing, shading, and terrain features. Additionally, pilot comments indicated that the inclusion of the roll arrow recovery guidance symbology and angle-of-attack displays helped the highly-experienced pilots to recover more easily from unusual attitudes and reduced reliance on external visual cues. The roll arrow was included because it is part of the SVS MASPS standard and there is significant likelihood of it being standard on all primary flight displays in the future.

Pilot preference was substantially biased toward the use of SVS, with top preference for the Industry Standard SVS2 condition. Feedback indicated that the awareness enhancement provided by the optical flow cues of the Industry Standard and Advanced virtual day-VMC displays was substantial (compared to Baseline and MASPS). Research evaluating SVS for UA recognition and recovery using comparative, repetitive testing techniques have also been performed, indicating no performance differences or preferences (Prinzel, 2017). These data, however, suggest that commercially trained pilots use SVS for attitude awareness with either comparable or improved performance to that of the existing baseline displays available today during operational flight profiles.

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